Numerical Simulation of Receptivity for a Transition Experiment

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SUMMARY OF RESEARCH: NAG-1-1976

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1 Executive Summary

The cost of fuel to overcome turbulence induced viscous drag on a commercial airplane constitutes a significant fraction of the operating cost of an airline. Achieving laminar flow and maintaining it over a large portion of the wing can significantly reduce the viscous drag, and hence the cost. Design of such laminar-flow-control wings and their practical operation requires the ability to accurately and reliably predict the transition from laminar to turbulent flow. The transition process begins with the conversion of environmental and surface disturbances into the instability waves of the flow by a process called receptivity. The goal of the current research project has been to improve the prediction of transition through a better understanding of the physics of receptivity.

The initial objective of this work was to investigate the specific stability and receptivity characteristics of a particular experimental investigation of boundary layer receptivity at NASA Langley [9]. Some simulation results using direct solutions of the linearized Navier–Stokes equations which modeled this experiment where presented in the 1999 APS DFD meeting [5]. However, based on these initial investigations, it became clear that to cover the vast receptivity parameter space required for a practical transition prediction tool, more efficient methods would be required. Thus, the focus of this research was shifted from modeling this particular experiment to formulating and developing new techniques that could efficiently yet accurately predict receptivity for a wide range of disturbance conditions.

From a very fundamental perspective, the receptivity problem involves nothing more than identifying the sensitivity of a flow to external disturbances – exactly the quantities that can be extracted from an appropriately formulated adjoint problem. In fact, an adjoint formulation can give the sensitivity of a flow to a wide range of disturbances simultaneously without having to resort to a vast number of initial value problems to cover a large parameter space.

In this research project we built upon our pioneering work in Linearized Navier–Stokes (LNS) methods [3] (which were the first published receptivity results based on the LNS) to include an adjoint formulation that automatically accounts for nonparallel and curvature effects while offering substantial improvements in computational efficiency. Current, adjoint methods have only been formulated under the simplifying assumption of parallel flow [8], which we have shown leads to large errors in predicted receptivity amplitudes for the critical three-dimensional instabilities near the leading-edge of swept wings [4]. In this project, we have formulation adjoint Navier–Stokes

and adjoint Parabolized Stability Equation methods that accurately account for both boundary layer growth and surface curvature. The accomplishments of this project include:

- Documented stability and acoustic receptivity results for experimental conditions outlined in original proposal using direct solutions of the linearized Navier–Stokes equations [5].
- Formulation and implementation of the adjoint Navier–Stokes for receptivity prediction [1]. We believe that this is the first published use of the adjoint Navier–Stokes for receptivity prediction.
- As part of this research, we have developed an improved outflow boundary condition for regular and adjoint Navier–Stokes receptivity calculations [2] which allows for dramatically smaller computational domains.
- We have formulated and implemented the adjoint Parabolized Stability Equations (APSE) for efficient receptivity prediction [1, 6]. In particular, this method has been demonstrated to be highly accurate through comparisons to adjoint Navier–Stokes simulations while retaining the efficiency of the Parabolized Stability Equations (PSE).
- Based on the success of both our direct and adjoint methods, we have developed a suite of computational tools for receptivity and transition prediction: LNS, ANS, PSE, and NPSE. These tools allow for accurate yet efficient simulation of the transition process from receptivity to the early stages of turbulence.

We are currently working on the following extensions to this research which have received funding from NASA-Langley under grant no. NG-1-2134.

- Extend the adjoint approach to predict nonlinear receptivity. This is of critical importance near the leading edge of wings where ice crystals or bug debris may directly initiate transition through a nonlinear receptivity path. We have proposed a novel iterative technique based on adjoint methods to address this problem
- Prediction of receptivity for a suite of existing experimental investigations. There are several experiments in the literature where, due to insufficient instrument sensitivity, the receptivity process is unknown. Our simulations will reveal the detailed physics of the receptivity process to help clarify the experimental findings.

In the following section, the detailed accomplishments of the current grant (NAG-1-1967) are reviewed including participating personnel, publications, and successes in obtaining follow-on funding.

2 Detailed Accomplishments

2.1 Participating Personnel

Three individuals participated on this project:

1. Prof. S. Scott Collis, Principal Investigator. This project funded 1 month of summer salary for the PI which enabled focused research on adjoint PSE methods for receptivity prediction.

2. Mr. Alexander Dobrinsky, graduate student. Alex started on this project in January of 1998 with a Bachelors degree in Physics from Rensselaer Polytechnic Institute. Since Alex started several months after the initiation of funding, a no-cost extension was requested which extended the grant end date till November 1999. This extension also allowed Alex to complete fundamental graduate courses in fluid mechanics which greatly improved his contributions to the project in the later half of 1999. This grant was extremely helpful in providing Alex with the research training experience needed to successfully complete his Ph.D. degree. Alex's Ph.D. thesis (anticipated in the Spring 2002) will include aspects of the research supported by this project in addition to follow-on funding that extends our receptivity investigations to include nonlinear effects. Alex recently won second place in the NASA-JSC AIAA student paper competition where he presented results from this research project [7].

3. Mr. Edward McCants. While not directly funded by the project, Ed was an undergraduate student in our BSME degree program who performed a semester long research project with me that explored acoustic leading edge receptivity which complemented this project.

2.2 Publications and Presentations

Work funded as part of this research program has been extensively disseminated through both written publications and presentations which are itemized below.

Publications

1. S. Scott Collis & Alexander Dobrinsky, 2000, *Adjoint Methods for Receptivity Prediction in Nonparallel Flows*, journal article under preparation.

2. Alexander Dobrinsky, 2000, *Receptivity Prediction using Adjoint Methods*, AIAA student paper competition, NASA-JSC, won second place in graduate student competition.

3. Alexander Dobrinsky & S. Scott Collis, 2000, *Adjoint Parabolized Stability Equations for Receptivity Prediction*, AIAA paper 2000-2651.

4. S. Scott Collis & Alexander Dobrinsky, 1999, *Evaluation of Adjoint Based Methods for the Prediction of Receptivity*, Proceedings of the 5th IUTAM Symposium on Laminar-Turbulent Transition, Springer.

5. Alexander Dobrinsky & S. Scott Collis, 1999, *Efficient Receptivity Predictions Based on the Adjoint Navier-Stokes Equations*, Bulletin of the American Physical Society, 44, (8), 27.

Presentations

1. Alexander Dobrinsky & S. Scott Collis, 1999, *Efficient Receptivity Predictions Based on the Adjoint Navier-Stokes Equations*, APS DFD Conference, November, 1999.

2. S. Scott Collis, 1999, *Adjoint Based Methods for Transition Prediction and Turbulence Control*, MMAE Graduate Seminar, Illinois Institute of Technology, December 8, 1999.

3. S. Scott Collis & Alex Dobrinsky, 1999, *The Evaluation of Adjoint Methods for Receptivity Prediction*, The 5th IUTAM Conference on Laminar Turbulent Transition, September, 13-17 1999.

4. S. Scott Collis & Alex Dobrinsky, 1999, *The Evaluation of Adjoint Methods for Linear and Nonlinear Receptivity Prediction*, Breakthrough Innovative Technologies Workshop, NASA Langley Research Center, September, 9 1999.

5. S. Scott Collis, 1999,*At the Crossroads of Receptivity and Flow Control*, ME Graduate Seminar, University of Houston, TX, April 1999.

6. S. Scott Collis & Craig L. Streett, 1997, *Computation of Acoustic Receptivity for a Transition Experiment*, Bulletin of the American Physical Society, 42, (11), 2173.

2.3 Follow-On Funding

The research funding by grant NAG-1-1967 was used to leverage additional funds to explore extensions of the current research and to supply computer resources for this investigation.

1. NASA Langley Research Center, Airframe Systems, *Nonlinear Receptivity and Bypass Transition in Three-Dimensional Boundary Layers*, 2/99 – 1/02, NG-1-2134, **PI** Collis.

2. NASA Ames Research Center, *Optimization of a Transition Simulation Code for the Origin 2000*, 10/98 – 9/99, 1500 node hours on SGI Origin 2000, PI Collis.

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[9] H. S. Kanner. *Evolution of an Acoustic Disturbance to Transition in the Boundary Layer on an Airfoil.* PhD thesis, Virginia Polytechnic and State University, 1999.